



Research Progress on the Livelihood Patterns of Ancient Central Asian Populations Based on Stable Isotope Analysis

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RESEARCH

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ABSTRACT

The Central Asian area was one of the core cultural areas in the ancient world and played a vital role in the process of world civilization and multi-ethnic integration. Hence, the reconstruction and restoration of the long-term food structures and the livelihood economy of the ancestors in this region have garnered significant attention. As the stable isotope data of the ancestors and animals' hard tissues in this region have continuously accumulated and enriched, the contours of the ancestors' food structure and the development and changes in their livelihood economy from the perspective of stable isotopes have become increasingly clear. In light of this, after collating and summarizing the published stable isotope data of humans and animals from the Bronze Age to the Iron Age in this region, and analysing the current hot research issues, it is noted that the sites where stable isotope analyses have been conducted are mostly concentrated in the northern part of Central Asia, while there are relatively fewer stable isotope achievements in the southern part. The research hotspots are centred on discussions of animal husbandry strategies, especially for goats and sheep, and the phenomenon of vertical grazing; the emergence and spread of C₄ plants in Central Asia; and there is less research on population migration using strontium isotopes. The results indicate that from the Neolithic Age to the Iron Age in the northern part of Central Asia, the livelihood patterns of the ancestors underwent considerable changes; in the southern part of Central Asia, since the second millennium BC, a relatively stable livelihood pattern with agriculture as the mainstay and animal husbandry as a supplement has formed, with little change.

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INTRODUCTION

Central Asia has been a core area of cultural exchange since ancient times, an important area of multi-directional cultural exchange linking Eurasia, not only a sensitive area with many geographical divisions, but also a crossroads of multi-ethnic cultural exchanges and human migrations. Stretching from the Arabian Peninsula to the Iranian Plateau and Central Asia, it can be considered a semi-arid region with limited potential for extensive rain-fed agriculture, concentrated around oases in well-watered areas, while livestock is more prevalent. The current core region of Central Asia includes Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan, and neighbouring regions include Turkmenistan, Afghanistan, northern Pakistan and northwestern India, Mongolia and northwestern Xinjiang, China. Given the variability of ecological environments, community composition and cultural characteristics in Central Asia, research on this region has received much attention. Currently, the region has become a hotspot for the study of the origins of nomadic cultures, the interaction and development of agricultural and pastoral cultures, human migration, and cultural exchange and integration.

As dietary structure is the basis for reconstructing the subsistence economy of the ancestors, as well as the source and entry point for understanding and recognizing colourful cultures, it is of great importance to explore the dietary structure of the ancestors in Central Asia. With the accumulation and enrichment of stable isotope data from human (and animal) bones from different periods in the region, the outline of the dietary structure of the ancestors in the region from the perspective of stable isotopes is becoming clearer and clearer.

Based on the published C and N stable isotope data of the ancestors and animals in the region, this paper is intended to analyse the current research hotspots and related results in Central Asia, to explain the food structure and livelihood economy of the ancestors in the region in different spatial and temporal frameworks, and to outline the characteristics and patterns of their changes and development. At present, the isotope research sites in Central Asia are mainly located in the Inner Asian Corridor, the steppes of Kazakhstan, the plains of southern Russia and the steppes of Mongolia, and the ages of the sites are mainly concentrated in the Bronze Age and the Iron Age, with a total of 29 sites from the Neolithic Age, 50 sites from the Copper and Stone Age and the Early Bronze Age, and 119 sites analysed by stable isotopes during the Bronze Age and 65 sites from the Iron Age. All site coordinates are located in [Figure 1](#). Details of the published carbon and nitrogen stable isotope data used in this paper are given in Supplement 1 and 2.

1. PATTERNS OF SUBSISTENCE OF CENTRAL ASIAN POPULATIONS IN THE NEOLITHIC

The Neolithic sites covered in the text date from about 5000 to 3000 BC ([Bazaliiskii 2003](#)), including the Avanashevo culture, Chemulchek culture-related sites.

Sites in Central Asia where stable isotope analyses have been done for the Neolithic period are mostly concentrated in the northern part of Central Asia, including the Altai region, the North Caucasus, the Lake Baikal region, and the Minusinsk Basin, and the specific carbon and nitrogen isotope results are shown in [Figure 2](#).

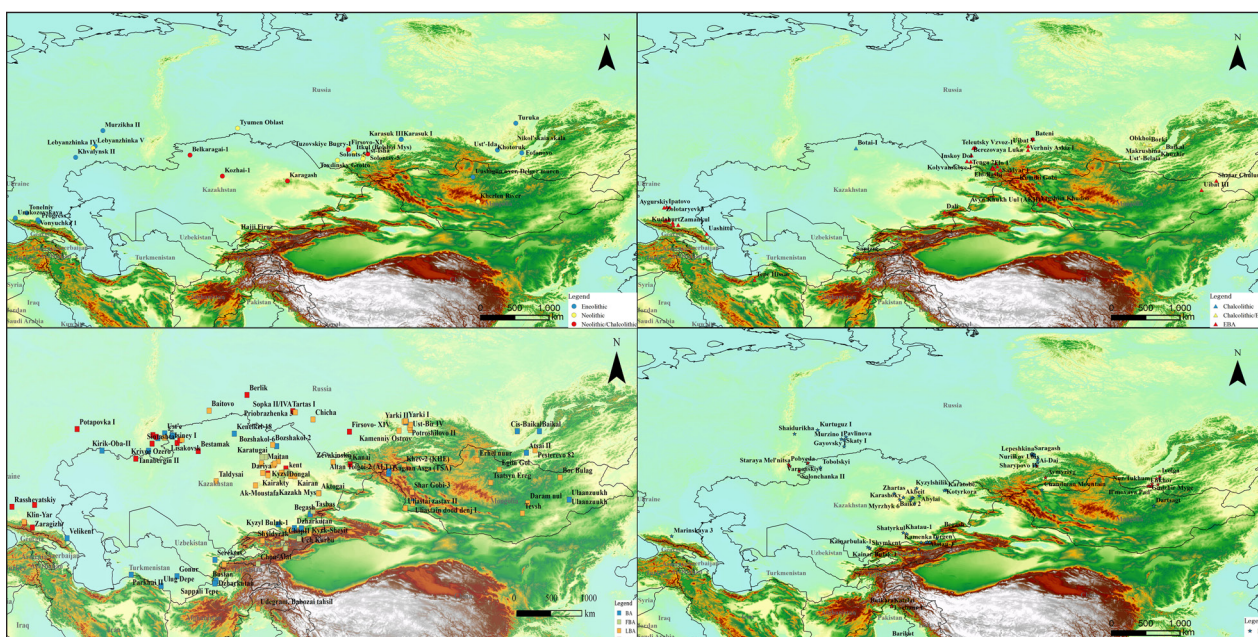


Figure 1 Sites in Central Asia that have undergone stable isotope analysis over time.

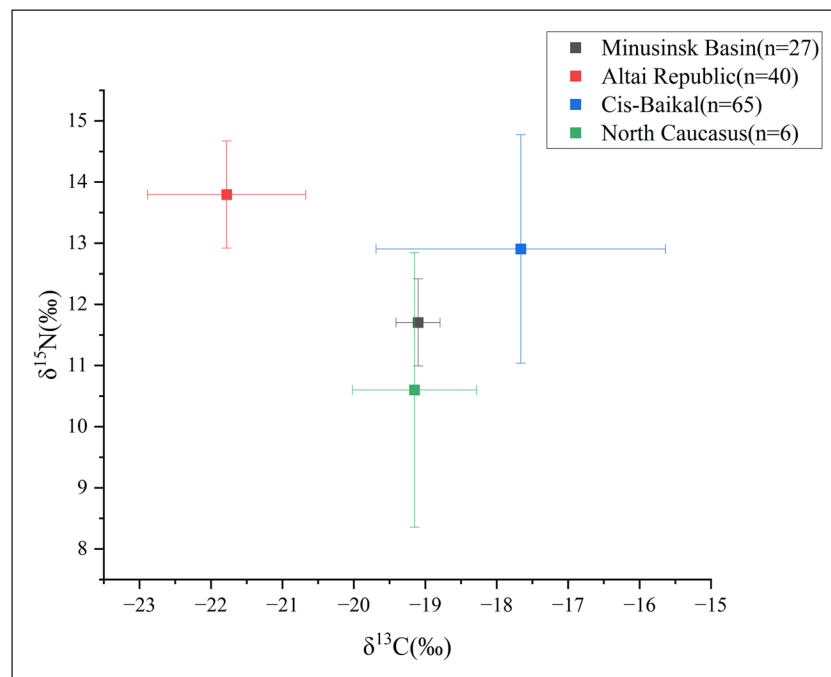


Figure 2 Bar plot of stable isotope data in Neolithic Central Asia.

As can be seen from [Figure 2](#), Neolithic Age humans had relatively low $\delta^{13}\text{C}$ and relatively high $\delta^{15}\text{N}$, with a mean $\delta^{13}\text{C}$ of $-21.78\text{‰} \pm 1.11\text{‰}$ ($n = 40$) for the Altai region population; $-19.1\text{‰} \pm 0.31\text{‰}$ ($n = 27$) for the Minusinsk Basin population, and $-17.65\text{‰} \pm 2.05\text{‰}$ ($n = 65$) for the Baikal region population, suggesting that populations ingested phytofoods that were all C3 plants, and that the proportion of intake in the three regions gradually decreased $17.65\text{‰} \pm 2.05\text{‰}$ ($n = 65$), with a gradual decrease in the range of $\delta^{13}\text{C}$ distribution, suggesting that the populations ingested phytophagous food, all of which were C3 plants, and that the three regions had a gradually decreasing percentage of intake, or possibly consumed animals that fed on C3 plants. In the Neolithic period, the mean deviations of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values between people and the fauna excavated from the site are small and do not constitute a more complete food chain, suggesting that people may have consumed a large amount of aquatic food along the food chain, and a similar situation was observed in the Bronze Age period ([Ventresca Miller & Makarewicz 2019](#)).

With the exception of the North Caucasus, where $\delta^{15}\text{N}$ values are low, the distribution of $\delta^{15}\text{N}$ values is more concentrated, and the first people present a higher percentage of animal protein intake; whereas the diversity of climates and environments in the North Caucasus may lead to a specific pattern of stable isotope values of terrestrial herbivores, which may affect the isotope values of humans who consume these animals ([Motuzaite Matuzeviciute et al. 2016](#)). The values of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ differences suggest that human and animal isotope values are closely related to geography and climate, with the northern dry steppe region having

the most abundant isotope values ([Ventresca Miller & Makarewicz 2019](#)).

Overall, Neolithic Central Asian humans had relatively higher $\delta^{15}\text{N}$ values than local terrestrial herbivores and carnivores, which may indicate that aquatic resources had a place in the Bronze Age diet of the region ([Svyatko et al. 2021](#)). The low $\delta^{13}\text{C}$ values indicate that the ancestors consumed a very small amount of phytophagous food, or fed on C3 plants, or ingested C3 herbivorous animals. However, research to date has focused only on the northern region of Central Asia, and no results have been published for the southern region of Central Asia, which makes it impossible to construct a characterization of Neolithic diets for the entire Central Asian region.

2. PATTERNS OF SUBSISTENCE OF CENTRAL ASIAN POPULATIONS IN THE BRONZE AGE

The Bronze Age sites analysed for stable isotopes are widely distributed, including the North Caucasus, the Urals, Siberia, the Kazakh steppe region, Mongolia, the Minusinsk Basin, along the Tien Shan Mountain range, southern Uzbekistan and south-eastern Turkmenistan. Carbon and nitrogen isotope results from Bronze Age sites where stable isotope studies have been carried out are presented in error bar graphs in [Figures 3 to 5](#).

2.1 PATTERNS OF SUBSISTENCE OF CENTRAL ASIAN POPULATIONS IN THE EARLY BRONZE AGE

Sites involved in the Early Bronze Age date from about 3200 BC to 2400 BC, including the Grazkovo culture (ca.

3000 BC to 2000 BC) of the Early Bronze Age cultures along the shores of Lake Baikal (Weber et al. 2010); the sites of the Vertical Cave Tomb culture (ca. 2600 BCE) in the Trans-Caucasus region (Shishlina et al. 2000); the Avanashevo culture (ca. 3200 to 2500 BCE) and Okunev culture (ca. 2500 to 1700 BCE) groups; and the Andronovo culture group in Kazakhstan (Dupuy et al. 2015).

As can be seen from Figure 3, in the Early Bronze Age, the $\delta^{13}\text{C}$ values of the ancestors in various regions, including the Minusinsk Basin, Lake Baikal, and the Altai region, were mostly distributed in the range of -20‰ to -18‰ , all of which indicate that the phytophagous food consumed by the ancestors was C3 plants, and the $\delta^{15}\text{N}$ values were mostly concentrated in the range of 10‰ – 13‰ , suggesting that the ancestors consumed a relatively high proportion of animal proteins. Compared to the Neolithic period, the combination of human $\delta^{13}\text{C}$ values suggests that the ancestors may have consumed some amount of aquatic products, and the lower $\delta^{15}\text{N}$ values indicate a decline in trophic level and a possible decrease in fish consumption, which may be related to the beginning of animal husbandry in the region and an increase in the consumption of animals grazed on mixed C3/C4 vegetation (Motuzaite Matuzeviciute et al. 2016). In contrast to the Neolithic, changes in human diets and a decrease in the variety of foods consumed during the Bronze Age may be the main reason for the changes in isotopic values. The North Caucasus, on the other hand, shows relatively different results, with $\delta^{13}\text{C}$ values between -18‰ and -16‰ at half of the sites in the region, indicating a mixed dietary composition of C3 and C4 phytophagous foods and a richer source of phytophagous foods compared to the Neolithic.

Early Bronze Age Avanashevo culture populations (Svyatko et al. 2017a) and populations from sites in

northern Kazakhstan (Ventresca Miller et al. 2014) relied predominantly on C3 plant and animal proteins; higher $\delta^{15}\text{N}$ values in males may reflect greater access to high nutrient levels of food, and higher nitrogen values in the populations may have been due to the inclusion of freshwater fish as part of the dietary intake (Svyatko et al. 2017a). The Kamennyi Ambar 5 site (Marchenko et al. 2015) of the Sintashta culture, on the other hand, shows a pattern of multi-resource husbandry, including animal husbandry, fishing, hunting, and collection of wild plant resources. Dietary differences between the Neolithic and Bronze Age in the Samara Valley region (Anthony et al. 2016) are significant, involving a reduction in freshwater fish consumption, and no corn cultivation was found. Most people in the central Kazakh steppe (Lightfoot et al. 2015) during the Andronovo period consumed few C4 plants, and many individuals had diets with higher $\delta^{15}\text{N}$ values, possibly consuming small quantities of freshwater fish (or animals that ate freshwater fish).

Overall, the subsistence structure of the populations of northern Central Asia during the Early Bronze Age showed different patterns in different regions, but all of them had a high protein diet. The populations of northern Central Asia adopted relatively similar strategies of animal use (Seregin et al. 2019), and animal husbandry, grazing in different vegetation areas and vertical grazing strategies appeared. The ancestors' phytophagous diet continued the Neolithic C3 plants, but the proportion of intake was lower than that of meat resources; freshwater fish resources were available in some areas, but the proportion was reduced; agricultural remains have not yet been found in northern Central Asia, and the ancestors had not yet begun to implement agricultural production strategies

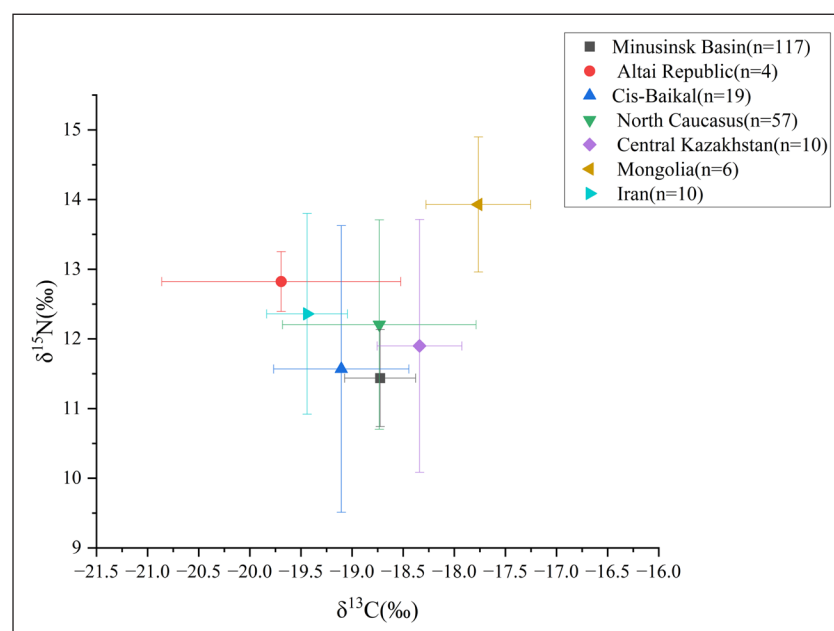


Figure 3 Error bar plot of stable isotope data in early Bronze Age Central Asia.

at this stage. And there are fewer studies of Early Bronze Age ancestral strategies in southern Central Asia.

2.2 PATTERNS OF SUBSISTENCE OF CENTRAL ASIAN POPULATIONS IN THE MIDDLE BRONZE AGE

The Middle Bronze Age includes sites dating from about 2500 BCE to 1500 BCE, and the major archaeological cultures include the Sintashta (Chechushkov & Epimakhov 2018) and Andronovo cultures (Grigoriev 2021); and sites such as the Bactria-Margiana Archaeological and Cultural Complex (BMAC) in south-central Central Asia (Lamberg-Karlovsky 1994).

As can be seen in Figure 4, the ancestors in different regions showed differentiation in their choice of plant and animal food. The structure of the $\delta^{13}\text{C}$ values of the ancestors in each region shows that they all presented C3 plant diets, but with different proportions.

The average Neolithic $\delta^{13}\text{C}$ value in the Altai region is $-21.78\text{‰} \pm 1.11$ ($n = 40$), which is lower than that of the Early Bronze Age ($-19.69\text{‰} \pm 1.17$ ($n = 4$)) and the Middle Bronze Age ($-19.49\text{‰} \pm 0.35$ ($n = 5$)), and the intake of phytophagous food by the ancestors became more frequent after entering the Bronze Age. The higher $\delta^{15}\text{N}$ value in the Neolithic than in the Bronze Age proves that the proportion of animal protein in the ancestral diet decreased. Taken together, the dietary characteristics of the ancestors in the Altai region from the Neolithic to the Bronze Age show changes over time, with the intake of phytophagous foods increasing and the proportion of animal proteins decreasing, but the proportion of animal proteins consumed is still much higher than that of phytophagous foods.

The wider distribution of $\delta^{15}\text{N}$ in the North Caucasus region suggests that the ancestors consumed different proportions of meat resources, while the lower nitrogen values may be the result of consuming foods from sources with low $\delta^{15}\text{N}$ protein values, such as horse-meat or by-products, or a higher intake of plant proteins than animal proteins. The overall higher $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of the ancestors in central Kazakhstan than in other regions proves that the ancestors had a higher intake of animal protein and consumed more C3 plants, whereas the ancestors of the sites in northern Kazakhstan had more stable $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, proving that there was little difference in the dietary status of the ancestors in the Kazakh steppe, all of them having a high animal protein and consuming a certain proportion of C3 foods. The economic cycle of animal feeding of Bronze Age and Early Iron Age herding groups living in the southern part of the Russian Plain was based on the seasonal variation of pastures, and the amount and type of forage intake of animals depended on the seasonal forage production in the pastures and the availability of different plant species (Shishlina, Sevastyanov & Kuznetsova 2018). This is similar to the seasonal migration practices of the Turgen site (Ventresca Miller et al. 2020) population for goats in central Kazakhstan. In contrast, there were differences in ancestral grazing practices at two sites, the Dzhetysay and Oguz cultural sites (Kurmaniyazov et al. 2023) in the lower Syr Darya, Kazakhstan, which may be related to the sedentary and semi-nomadic lifestyles of these groups. Many of the herbivores had elevated $\delta^{13}\text{C}$ values, which may indicate consumption of C4 vegetation or *Panicum miliaceum* and *Setaria italica* as forage but may also be related to the fact that their isotopic values were affected by the arid environment.

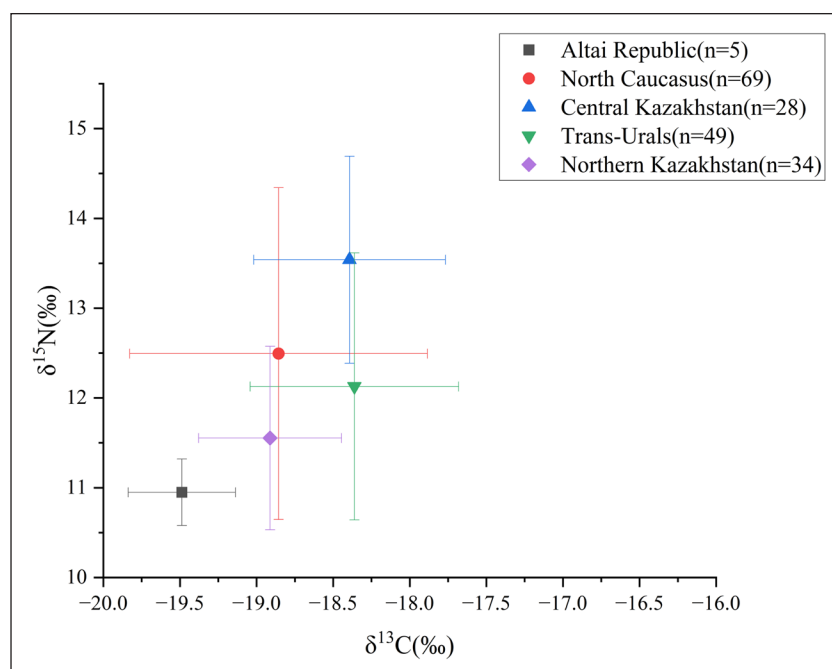


Figure 4 Error bar plot of stable isotope data in the Middle Bronze Age Central Asia.

2.3 PATTERNS OF SUBSISTENCE OF CENTRAL ASIAN POPULATIONS IN THE LATE BRONZE AGE

Sites involved in the Late Bronze Age date from about 1900 to 1400 BCE, and the Final Bronze Age from about 1400 to 1000 BCE (Baumer & Novák 2019). During this period, the specialized pastoral economy extended from the Ural Mountains to the Tien Shan, throughout northern Central Asia (Spengler et al. 2017; Hermes et al. 2022), and the main archaeological cultures were the Andronovo and Karasuk cultures (Legrand 2006).

As can be seen in Figure 5, the isotopic evidence suggests that the Bronze Age diet in central Kazakhstan was more diverse than traditionally thought. This is complemented by a study by Svyatko (2017b) which suggests that the diet of the Tasmola culture population included C4 plants through isotopic analysis. This provides evidence for the spread or cultivation of *Setaria italica* in central Kazakhstan during the Early Iron Age. In contrast, the $\delta^{13}\text{C}$ value of $-18.05 \pm 0.91\text{‰}$ ($n = 11$) for the population of the site in the southern Central Asian region indicates a phytophagous diet of C3 plants, and the $\delta^{15}\text{N}$ value of $13.05 \pm 1.34\text{‰}$ ($n = 11$) indicates a lower percentage of animal protein intake compared to the northern Central Asian region.

There are more stable isotope research results in the North Caucasus, from the Neolithic to the Iron Age (Lightfoot et al. 2015; Narasimhan et al. 2018). As can be seen from the error bar diagram, the results of the $\delta^{15}\text{N}$ values of the ancestors show little change from the Neolithic to the Iron Age, concentrating on the

distribution in the range of 10‰–12‰, where the $\delta^{15}\text{N}$ value of the Early and Middle Bronze Ages is higher than that of the other periods. The results of the $\delta^{13}\text{C}$ values of the ancestors show that there were differences in the intake of phytophagous food by the ancestors, in which the overall $\delta^{13}\text{C}$ values increased over time from the Late Bronze Age to the Early Iron Age. Overall, the intake of animal protein was higher than that of phytophagous foods.

The $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values of the ancestors in the Minusinsk Basin did not change much from the Neolithic to the Early Bronze Age, while they should have changed significantly up to the Middle Bronze Age, but the loop could not be closed perfectly because the results of the stable isotope studies did not yet cover the Middle Bronze Age. Up to the Late Bronze Age and Early Iron Age, the $\delta^{13}\text{C}$ values of the ancestors show large differences with a wide range of fluctuations, and the $\delta^{13}\text{C}$ values show a tendency to increase, indicating that the use of agriculture gradually matured. During the Iron Age, the $\delta^{13}\text{C}$ values of the ancestors were stable at -16‰ to -13‰ , and the plant foods consumed by the ancestors changed compared to the early stage, which may indicate that *Setaria italica* agriculture was introduced to the region from China and gradually developed and stabilised.

The consumption of C4 plants, most likely domesticated *Setaria italica*, was present in the populations of Bronze Age sites in the mountainous regions of southern Kazakhstan. In contrast, the diets of Bronze Age individuals in northern Kazakhstan had a lower intake of C4 plants. This suggests that there are

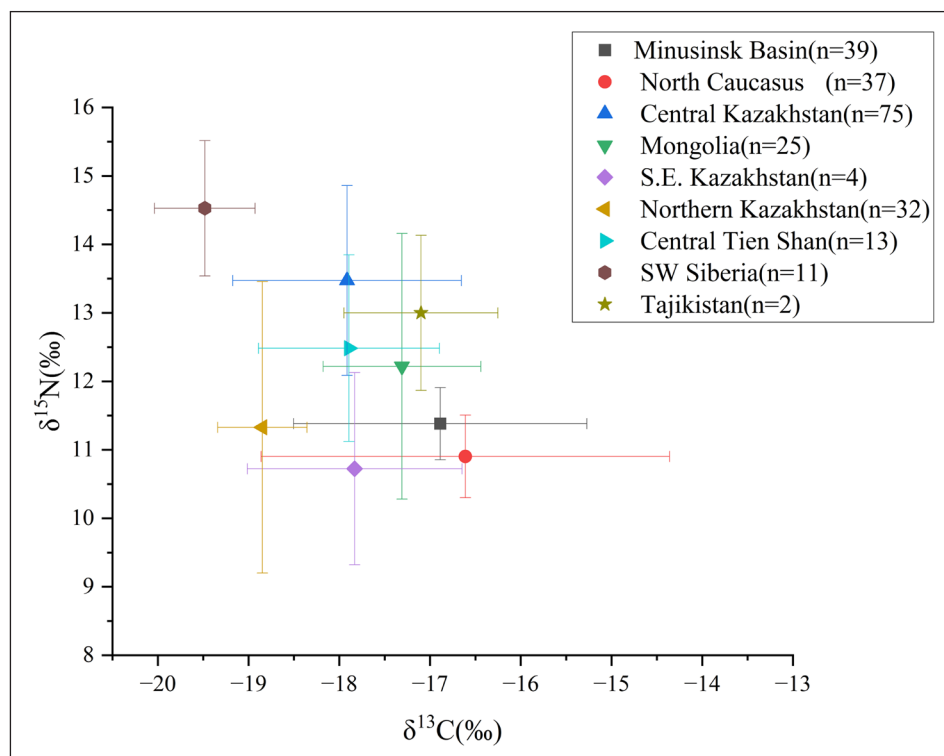


Figure 5 Error bar plot of stable isotope data in Late Bronze Age and Late Bronze Age Central Asia.

significant differences in the extent of cereal cultivation and dependence between geographical regions. There was diversity in ancestral diets in the Middle Tien Shan region from the Bronze Age to the Turkic period, and there was no single dependence on animal husbandry (Ananyevskaya et al. 2021). The diversity of stable isotope results within and between sites suggests that people at this time may have adopted a variety of subsistence strategies, including agriculture, animal husbandry and possibly fishing. The populations of the Amu Darya valley in southern Central Asia, on the other hand, showed a dietary structure based on C3 plants (Liu K et al. 2020) supplemented by animal proteins during the Late Bronze Age, showing a subsistence pattern based on wheat farming supplemented by animal husbandry. The dependence on different animal subsistence may have influenced human isotope values in different ecological zones of northern Central Asia. Zooarchaeological data suggest (Outram et al. 2012) that the inhabitants of northern Kazakhstan and the Trans-Ural region were more dependent on cattle and horse products (Outram et al. 2011), whereas the inhabitants of central and south-eastern Kazakhstan were dependent on mouflon meat production. This is likely to be reflected in the isotopic expression of the human populations studied, resulting in lower $\delta^{13}\text{C}$ values in northern Kazakhstan and the Trans-Ural region, and lower $\delta^{13}\text{C}$ values in central and south-eastern Kazakhstan with higher $\delta^{13}\text{C}$ values. Altitudinal effects due to certain grazing strategies, such as the vertical transhumance grazing practised in the mountainous regions of Altai and south-eastern Kazakhstan (Lightfoot et al. 2015), may also

be responsible for the increased $\delta^{13}\text{C}$ values in animal tissues.

Taken together, these studies show that subsistence patterns in the Neolithic/Chalcolithic to Bronze Age in the southern plains of Russia were little changed, with animal husbandry dominating overall, with a reliance on C3 plants and terrestrial animal proteins, and with the consumption of freshwater fish occupying an important place over a wide area. Subsistence strategies during the Bronze Age in central Kazakhstan were not solely concerned with pastoralism, but fishing and cultivation were important components of subsistence strategies, and the increasing consumption of millet over time may be indicative of the increasing role of agriculture in the economy of the region.

3. PATTERNS OF SUBSISTENCE OF CENTRAL ASIAN POPULATIONS IN THE IRON AGE

The Early Iron Age is defined as the period from 1300 BCE to 900 BCE, and the Late Iron Age extends until 300 BCE (Baumer & Novák 2019). The sites where stable isotope studies have been done in the Iron Age are widely distributed, and the carbon and nitrogen isotope results from each region are now made into error bar charts to be analysed in Figures 6 and 7.

The diet of the ancestors in the central and northern regions of Kazakhstan did not differ much in the Bronze Age (Matuzeviciute et al. 2015), with $\delta^{13}\text{C}$ values ranging from -20‰ to -18‰ , whereas the Bronze Age in the south-eastern region showed higher $\delta^{13}\text{C}$ values

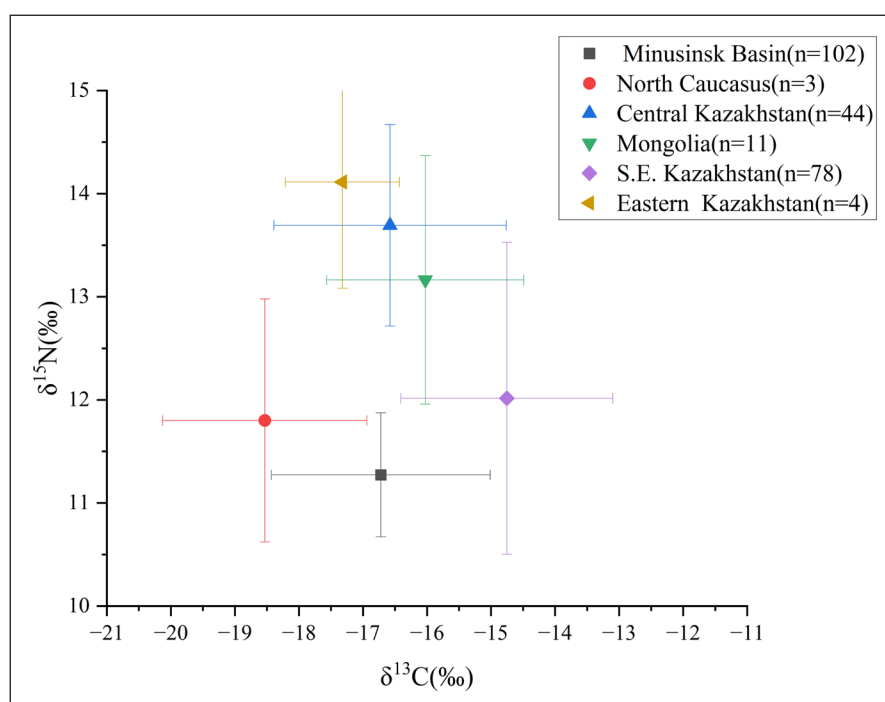


Figure 6 Error bar plot of stable isotope data in early Iron Age Central Asia.

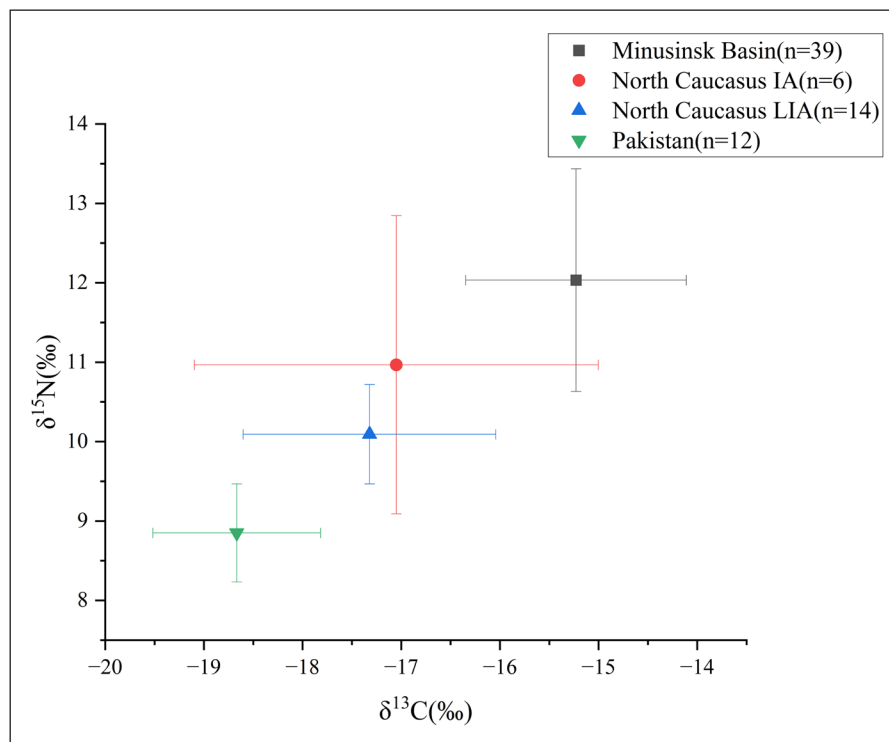


Figure 7 Error bar plot of stable isotope data in Iron Age Central Asia.

($-15.56\text{‰} \pm 1.78$ ($n = 11$)), reflecting a higher proportion of C3 plants and more phytophagous food intake than in other regions; the $\delta^{13}\text{C}$ values in the Early Iron Age ($-14.75\text{‰} \pm 1.16$ ($n = 4$)) in the Early Iron Age are higher than those in the Late Bronze Age ($-17.83\text{‰} \pm 1.18$ ($n = 4$)), which shows that the proportion of phytophagous food intake increased over time, that they were more selective about plants, and that the population's dependence on agriculture gradually increased (Privat 2004; Bocherens et al. 2006; Murphy et al. 2013).

Early Iron Age Scythian world groups had a predominantly nomadic economy, with corn and fish as the main components of their diet. This complex model of a mobile nomadic economy included significant agricultural activity and the use of freshwater fish. In contrast, the diets of different regions of Kazakhstan showed differentiation, with higher $\delta^{13}\text{C}$ values in the southern region compared to the central and eastern regions, demonstrating that the southern region used a variety of food-acquisition strategies at that time, and that agriculture and nomadic lifestyles were more closely linked. Relatively contemporaneous studies in southern Kazakhstan show that the overall range of human $\delta^{13}\text{C}$ values during this period was large, from -20‰ to -13‰ , which may be because individuals mainly consumed C3 crops (wheat, barley, and rice) or C4 crops at sustained intensity (Hermes et al. 2018).

The southern Central Asian region, on the other hand, is less studied and dominated by studies of Iron Age and later sites. Stable isotope analyses of Iron Age sites in southern Central Asia show that (Bocherens et al. 2006) Iron Age and later humans appear to have relied mainly

on C3 plants with limited herbivore proteins such as meat or dairy products. The recipes of the ancestors of the Rabat cemetery are characterized by a relatively high intake of animal proteins, with plant foods derived from C3 plants such as wheat (Liu K et al. 2020). From the late 2nd century BC to the early 1st century AD, the Yuezhi people who migrated westwards into the region of Uzbekistan adapted to the local environment and developed a mixed agricultural and pastoral economy, mainly pastoralism. Combined with phytoarchaeological evidence from related sites in southern Central Asia (Spengler et al. 2018; Shapulatov 2023), it suggests that by 4000 years ago a diverse agricultural system had emerged in the region, including food crops, fruit and tree crops, and fibre crops, combining elements from the east and west (Ankushcheva et al. 2021). Bronze Age and Iron Age populations of southern Central Asia showed remarkable diversity and complexity in their animal husbandry patterns. During the Bronze Age, the inhabitants of southern Central Asia reared mainly cattle, sheep and goats, which were not only an important source of food but also provided dairy products, skins and means of transport. At the beginning of the Iron Age, the main domesticated animals of the ancestors were *Bos taurus*, *Camelus dromedarius*, *Equus* (Outram et al. 2011), *Ovis/Capra*, *Equus asinus* and other animals (Peters et al. 2024). For phytophagous animals, such as domestic cattle, sheep and goats, the main forage was C3 plants close to the habitat and the dietary pattern was largely unchanged; dogs had a diet similar to that of humans and were probably fed mostly on human leftovers. Livestock production continues to develop in

southern Central Asia, but a more diverse livestock mix has emerged. In addition to the traditional cattle, sheep and goats, *camelus bactrianus* were domesticated on a large scale, especially in the Iranian plateau and the Central Asian highlands. These animals were not only used for transport, but also contributed to the formation of caravan networks in the desert, making oases important supply stations.

It is easy to see that $\delta^{13}\text{C}$ values in the Late Bronze Age to Early Iron Age show large differences in all regions, which is due to the spread of *Panicum miliaceum* and *Setaria italica* in Central Asia. The emergence of domesticated C4 plants in Central Asia and the westward route of *Panicum miliaceum* and *Setaria italica* has been a hot research topic in recent years. In Central Asia, many scholars have analysed the route of *Panicum miliaceum* and *Setaria italica* dispersal, and stable isotopes of human and animal bone collagen from the Early Bronze Age to the Turkic period in Kyrgyzstan indicate that the high valleys of the Inner Asian Mountain Corridor (Matuzeviciute et al. 2022; Ventresca Miller et al. 2023) were the channels of *Panicum miliaceum* and *Setaria italica* dispersal in Eurasia. Analyses of possible *Panicum miliaceum* and *Setaria italica* dispersal routes based on carbon and nitrogen isotope data from the North Caucasus, the Minusinsk Basin and the Mongolian Plateau region (Ventresca Miller & Makarewicz 2019) suggest that C4 plants only became an important component of the Late Bronze Age Karasuk and Early Iron Age Tagalvanian diets (Svyatko et al. 2013). Results of stable isotope analyses of samples from Late Bronze Age and Early Iron Age sites in central, southern and eastern Kazakhstan suggest that C4 plants were consumed in central Kazakhstan as early as the Late Bronze Age and that this trend continued into the Early Iron Age (Ananyevskaya et al. 2018). Ancestors who consumed C4 plants were usually males in high-ranking burials (Ananyevskaya et al. 2018), which may indicate the development of C4 agriculture in the region and the production of C4 crops such as *Panicum miliaceum* and *Setaria italica* as a status symbol. The extent to which herbivore products, fish and cultivated plants contributed to the diets of Bronze Age and Iron Age populations in Kazakhstan was investigated by compound-specific nitrogen isotope analyses of amino acids, and C4 plants appear to have contributed more to the survival of populations in southeastern Kazakhstan than to the diets of the other human populations analysed (Itahashi et al. 2020).

Taken together, cultivated C4 plants were circulating as human and animal food among the mountain populations of Central Asia as early as the third millennium B.C. The use of *Setaria italica* and *Panicum miliaceum* was initially sporadic and low-intensity, but the origins of these plants are still unclear and there is currently no direct evidence for the local cultivation of C4 crops such as *Panicum miliaceum* and *Setaria italica*.

It may have occurred as early as the end of the third millennium BC in the Minusinsk Basin. During the Early Bronze Age, C4 herbivores in Kyrgyzstan and eastern and central Kazakhstan may have had a special status and acquired burial rites and grave goods atypical for the period (Matuzeviciute et al. 2022). The initial spread of *Panicum miliaceum* and *Setaria italica* agriculture across the Inner Asian mountains coincided with an overlap between animal husbandry and crop cultivation, suggesting that pastoralism was an important factor in the westward spread of millet from agrarian societies. From the middle of the second millennium BC, *Panicum miliaceum* and *Setaria italica* consumption increased dramatically throughout Eastern Europe; for example, mature agriculture existed in southern Kazakhstan by 1800 BC (Ananyevskaya et al. 2018) and the C4 plant had become a regular food source in southern Kazakhstan and could have been consumed directly by humans. The exception was the Mongolian steppe, where *Panicum miliaceum* and *Setaria italica* were not consumed until the end of the first millennium BC. The emergence of complex transregional political networks during the transition to the Iron Age may have facilitated the rapid transfer of varieties across the steppe. For example, the earliest appearance of C4 plants in central Kazakhstan coincided with a period of major social and economic change in the region, which contributed to the spread of C4 crops across Central Asia.

During the Early Iron Age, stable isotope results show that millet agriculture was already widespread, and a certain degree of consumption of C4 plants was observed in the vast majority of the territory of Kazakhstan, with people in the south of the country consuming more C4 plants than people in the centre of the country during the same period. From the early Iron Age until the Turkic period, C4 plants became a major component of the human food web. This may reflect the gradual development and spread of agricultural practices and the increased reliance on C4 crops, especially millet. The increase in nitrogen content in the human food chain may indicate a change from a cereal-based diet to one based on meat and dairy products.

4. PROBLEMS AND DEVELOPMENT TRENDS

Based on the above analysis of the subsistence patterns of people in Central Asia in different periods, it can be seen that the results of stable isotope research in Central Asia can be mainly divided into the following contents: Carbon and nitrogen isotope analysis of individual sites or a particular region to understand the ancestors' subsistence and economic patterns; the emergence and spread of C4 signals in Central Asia, including the important sites and important time nodes; and the use

of carbon and oxygen isotopes as a research tool to study the ancestors' animal feeding strategies, vertical grazing issues, and the development of the C4 signal. The study of ancestral subsistence strategies and vertical grazing using carbon and oxygen isotopes as a research tool. The study of the subsistence pattern and migration of the population in this region will provide basic materials for solving many global archaeological problems, including the origin of the nomadic economy, the exchange and collision of agricultural patterns between East and West Asia, and the exchange and integration of ethnic groups in the Bronze and Iron Ages, etc.

The results of carbon and nitrogen stable isotope research have been used to reconstruct the dietary changes of the ancestors from the Neolithic to the Iron Age. The results show that the Neolithic ancestors consumed very little C3 food or animals that fed on C3 plants; the intake of animal proteins was high and freshwater fish resources may have been consumed in some areas. The animal and plant diets of Early Bronze Age ancestors were not very different from those of the Neolithic, and the intake of freshwater fish resources was reduced. In the Middle Bronze Age, ancestral diets varied from region to region, with an increase in the proportion of plant foods in northern Kazakhstan compared to regions further north, such as the North Caucasus, and little difference in feeding strategies for animals. In the Late Bronze Age, C4 plant food began to appear in some regions, such as central Kazakhstan, and in the Iron Age, the ancestors' food choices gradually increased and their diets became more diversified. From the Bronze Age to the Iron Age, northern Central Asia experienced a change from predominantly pastoralism to the gradual integration of agriculture and fishing. This change reflects not only environmental adaptation, but may also be related to social structure, technological development and cultural exchange. The increase in *Panicum miliaceum* and *Setaria italica* consumption over time may indicate the increasing importance of agriculture in the region's economy.

There were differences in the way ancestors kept animals. Overall, the Bronze Age and Iron Age strategies for rearing goats and other animals in northern Central Asia differed, but in general there was little change, and there was summer transhumance to alpine pastures in ancestral animal husbandry. The diet of goats was dominated by C3 plants. Changes in the dietary intake of the animals may have depended on the location of the pasture or may have been a factor related to environmental changes over time. Due to the pasture and grazing management practised by ancient populations, cattle, sheep and horses had different feed intakes over time and space, reflected in differences in the isotopic values of different species, and isotopic differences observed in animal bones suggest that local

herders developed pastures located in different climates. Thus, variations in $\delta^{13}\text{C}$ values in human populations from different regions of northern Central Asia may be influenced not only by direct dietary intake of C4 plants, but also by differences in the extent of consumption of cattle, horse and livestock products in different parts of Central Asia, and whether or not high-altitude transhumance grazing was practised in the region.

However, there are still some shortcomings. The carbon and nitrogen stable isotope research results in the southern region of Central Asia are fewer and limited to the Late Bronze and Iron Ages, and it is not possible to sort out the changes in the ancestral dietary conditions from the isotopic perspective, and the climatic characteristics of the southern region of Central Asia are different from those of the northern region of Central Asia. The stable isotope research on the sites of the southern region of Central Asia should be intensified in the following period in order to construct a comparison of the dietary patterns and living conditions of the ancestors of the Central Asian region, including subsistence patterns. This will play an important role in the study of the spread of millet and barley.

Stable isotope analysis of ancestral subsistence and economic patterns is relatively mature, but in recent years studies on the mechanism of stable isotope analysis have shown that environmental factors influence carbon isotopes, such as high $\delta^{13}\text{C}$ values in arid areas, which should be taken into account when analysing the phytophagous food sources of populations or animals. As many regions in Central Asia are arid, stable isotope analyses should take into account the influence of environmental factors on isotope values and should be combined with visual evidence, such as plant and animal archaeology, to comprehensively analyse the subsistence and economic strategies of ancestors and their animal feeding strategies.

Isotopic studies in Central Asia have mostly focused on carbon, nitrogen and oxygen isotopes, and strontium isotope analyses of population exchange and migration are extremely rare. Strontium isotope analyses have only been carried out for the Jirzankal cemetery, an Early Iron Age cemetery on the eastern Pamir Plateau, in northern Central Asia (Wang et al. 2016), which shows frequent migration and high mobility of the Pamir Plateau ancestors 2500 years ago. The Hunnic population of the ancestors of the Baga Gazaryn Chuluu site (Makarewicz et al. 2024) shows higher mobility for the purpose of political consolidation of spatially dispersed mobile pastoral communities to consolidate their position. Where the southern regions of Central Asia, especially Turkmenistan and central Uzbekistan (Kroll et al. 2022), had high rates of migration and mobility in the Early Bronze Age, the Late Bronze Age is characterized by a decline in migration and mobility, with a predominantly sedentary

lifestyle and frequent movement within small areas, reflecting a subsistence pattern in which agriculture was dominant and pastoralism complementary. The Surkhan Valley and other sites in southern Tajikistan suggest that individuals migrated with active mobility over a wide area of southern Central Asia. For a region with frequent movement of peoples, the potential for research on migration in Central Asia using strontium isotope analysis is highlighted.

Central Asia is a region of exchange between maize agriculture in East Asia and wheat agriculture in West Asia, and the study of people's livelihoods in different regions of Central Asia can enhance the study of the routes and time periods of the spread of maize agriculture to the west and wheat agriculture to the east from different perspectives. While the routes and time periods have been clarified over the past two decades, some of the time periods are still unclear, and we can continue to strengthen agro-cultural exchange from the perspective of stable isotopes in the future. The analysis and study of the routes and timing of C4 signals in Central Asia will remain a hot topic in the future.

Carbon and oxygen isotopes are more mature in the study of animal feeding strategies, but there are not many such studies in Central Asia; the overall feeding strategies of the southern region of Central Asia are different from those of the northern region, but there are not too many such studies on animal feeding strategies in southern Central Asia, so we can increase the number of relevant studies in Central Asia in the future.

5. CONCLUSION

The following lessons can be drawn from the above synthesis and analysis:

1. From the Neolithic to the Iron Age, changes in ancestral lifestyles and economies were greater in northern Central Asia than in the southern region. In the northern part of Central Asia, due to climate, environment, cultural influences and many other factors, the mode of production is constantly changing, and individual regions are engaged in wheat or maize agriculture; crops are mainly barley, and other crops do not have a major impact on wheat agriculture. In this part of the region, the subsistence pattern in the Neolithic period was mainly based on the fishing and hunting economy; in the Early Bronze Age, the proportion of fishing and hunting economy of the ancestors in northern Central Asia decreased and the population began to focus on animal husbandry, with a high proportion of terrestrial animal protein, including goats, sheep, horses, cows and other animals, and phytophagous food, including C3 plants; In the Late Bronze Age to Early Iron Age, most regions in northern Central Asia showed more consistent changes in $\delta^{13}\text{C}$, with a higher proportion of $\delta^{13}\text{C}$ and a higher proportion of $\delta^{13}\text{C}$. The Late Bronze Age to Early Iron Age in most areas of northern Central Asia shows a more consistent change, with a significant increase in $\delta^{13}\text{C}$ values and clear differentiation within the population, indicating an increase in the intake of phytophagous foods and an increase in the choice of crops by the first people, which shows an increased reliance on agriculture by the population of northern Central Asia during this period, but still dominated by animal husbandry, with a higher proportion of terrestrial animal protein, and the appearance of C4 plants in the phytophagous diet, which gradually spread from the Xinjiang area of China into Central Asia, and slowly increased. The scale of enjoyment gradually expanded, the proportion of population consumption increased, and by the Iron Age, the area of corn consumption also gradually expanded.
2. The southern region of Central Asia, on the other hand, is less studied in the Bronze Age, the Iron Age and the historical period of the mode of subsistence is based on agriculture, with animal husbandry, phytophagous food is mainly based on C3, and animals are mainly terrestrial animal proteins, and there is a certain amount of consumption of secondary products, and there was already large-scale irrigated agriculture about 4,000 years ago in the Amu Darya region and other early city-states, and a long line of inheritance. Despite the impact of crops such as millet and rice, the composition of food crops remained very stable, and the agricultural structure did not change significantly from that formed after the Iron Age.
3. According to carbon and oxygen isotope analyses of the ancestors' animal feeding strategies, the results of the study show that the ancestors in northern Central Asia mostly chose different ways to improve the survival rate of animals in order to increase the production of secondary products such as wool and milk, including winter births of animals, changing the winter pasture, and choosing different types of pasture in summer and winter. Since the emergence of relatively stable agriculture and pastoralism in southern Central Asia 4000 years ago, there has been little change in the production methods of the population, and the ancestors mainly reared cattle, sheep and other animals.
4. Central Asia has been a zone of frequent migration since ancient times, but there are fewer studies on migration in Central Asia, and the strontium isotope method is more mature, so in the future we can increase the research on migration in Central Asia and build a strontium isotope atlas of Central Asia.

DATA ACCESSIBILITY STATEMENT

Data will be made available on request. All data is available in the main document or referenced publications.

ADDITIONAL FILES

The additional files for this article can be found as follows:

- **Supplement File 1.** Carbon and nitrogen stable isotope error bar data of ancient populations in Central Asia. DOI: <https://doi.org/10.5334/srah.19.s1>
- **Supplement File 2.** Detailed carbon and nitrogen stable isotope data for ancient Central Asian populations.. DOI: <https://doi.org/10.5334/srah.19.s2>

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COMPETING INTERESTS

The authors have no competing interests to declare.

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